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CHAPTER I

INTRODUCTION

One of the primary responsibilities of the operational meteorologist is to issue warnings for possible occurrences of severe weather. These warnings allow the meteorological customer and the public time to take precautionary measures, either in terms of a reduction of property loss or savings in human suffering. To do this job effectively, the meteorologist relies heavily on weather radar to detect, identify, and track convective storms. Conventional radar does not detect or identify severe weather associated with convective activity, but rather its presence is inferred based on the meteorologist's interpretation of radar backscatter information. Doppler radar has been shown to be a better tool than conventional radar for severe storm identification ~~(see~~ Donaldson et al., 1975b and Burgess, Bonewitz, and Devore, 1978), but Doppler radar is not operationally deployed for thunderstorm surveillance. Until Doppler radar becomes operationally available to the practicing meteorologist, conventional radar must be used to identify those storms capable of producing severe weather at the surface.

The concept of using radar signatures to define those thunderstorms likely to produce severe weather has

existed for over two decades. The most frequently-used conventional radar signatures to define these destructive storms include the maximum radar reflectivity, the maximum height of the radar echo, and the presence of persistent echo configurations. The reflectivity is a measure of the size and concentration of water droplets and ice particles within the contributing volume of the storm system; the greater the size and concentration, the greater the amount of energy backscattered and the more intense the radar backscatter signal. The height of the radar echo indicates the strength of the central updraft, the tallest storms associated with the strongest updrafts. Finally, persistent echo configurations are radar echo signatures empirically associated with severe thunderstorms. However, these configurations do not always unambiguously define severe weather occurrences. Pearson (1975) stated that these signatures, reviewed by Whiton (1971), are present less than 30 per cent of the time when tornadoes occur. The feasibility of using the other conventional radar backscatter parameters to define severe thunderstorms has yet to be fully established since conflicting results exist as to which parameters are most reliable.

Donaldson (1958, 1959, 1960, 1961), using 3.2-cm radar in New England, found that the magnitude of the maximum reflectivity and the vertical distribution of reflectivity were useful indicators of severe thunderstorms.

He found a reflectivity maximum near 20,000 ft indicative of occurrences of large surface hail and tornadic activity. The findings of Inman and Arnold (1961) in Texas and Wilk (1961) in Illinois corroborated Donaldson's findings, but heights of the reflectivity maxima were found between 20,000 and 30,000 ft in Texas storms, while 10,000 to 24,000 ft was the range for Illinois severe storms. Since the radar wavelength used in all studies was the same, disparities in results were believed due to the different geographical locations of the studies. The different heights of echo tops associated with the occurrence of surface hail also reflected these differences. In New England 43,000 ft was considered indicative of hail-producing storms, but 48,000 ft was found to be the height of echoes associated with surface hail in Texas (Sanford, 1961).

Investigations of hailstorms in the High Plains and Alberta by Douglas (1961) and Schleusener and Marwitz (1963) revealed that the magnitude of the maximum reflectivity was a more reliable indicator of hailstorm identification and that this signature was indicative of the size of hailstones aloft. Further, the studies found that echo tops associated with hailstorms in this geographical region were 10,000 ft lower than for New England storms.

Studying hailstorms in New England with 10-cm

radar, Geotis (1961, 1963) found no reflectivity maximum aloft, but that the reflectivity at all levels is greater in storms associated with hail, the maximum reflectivity occurring in the lowest 15,000 to 20,000 ft of the storm. Stem (1964) also inferred that the reflectivity maximum was wavelength-dependent. Speed (1965) suggested that the reflectivity maximum may be due to significant attenuation at the 3.2-cm wavelength as well as to the presence of water-coated or spongy hail.

Operational studies using WSR-57 10-cm radars were conducted at several locations in the central U. S. during the early 1960s. Results of studies by Hamilton (1963) in Kansas City, Whalen (1963) in Minneapolis, and Conte (1964) and Williams (1965) in St. Louis were highly dependent on the internal structure, geographic location, and season of occurrence of the storms. The consistent result obtained from these studies was that the further north the study area the lower the echo top of storms that produced hail. However, Geotis (1963) and Hiser (1958) found severe weather occurrences associated with echo tops well below suspected levels, so no unique relationship exists between echo top heights and severe weather occurrences.

The ability of thunderstorms to penetrate the tropopause has also been investigated as a possible characteristic for determining the severe weather

potential of the storm. Results of studies by Donaldson, Chmela, and Shackford (1960), Inman and Arnold (1961), Pautz and Doloresco (1963), Long et al. (1965), and Long (1967) indicated some correlation between severe storm occurrences and tropopause penetrations, but due to the varied geographic locations of the studies no conclusive judgments are possible.

Recent research to correlate radar signatures and surface weather occurrences has centered on the occurrence of hail in the High Plains. Boyd and Musil (1970) and Dennis et al. (1971) reported that the best indicator for hail occurrences at the surface was the 10,000 ft (3 km) reflectivity maximum for radar operating at 10-cm wavelengths. However, results of these studies have not been applied to other occurrences of severe weather. Rennick (1971) confirmed that high reflectivities near 3 km indicate hail within the storm, but added nothing to the previous results.

Lemon (1977a,b) developed a new method of severe thunderstorm identification by conventional radar. The method uses storm structure as the tool to define the severe weather potential of the storm. This concept is very promising since it combines various radar detectable features into a unified technique for severe storm identification.

Following the leads of preceding severe thunder-

storm investigations by Donaldson (1958, 1959, 1960, 1961), Inman and Arnold (1961), Wilk (1961), Lemon (1977a,b), etc., this investigation seeks to define geographically and seasonally dependent values of radar detectable signatures associated with severe weather. Variations among these detectable signatures, as well as the thunderstorm structure, have been identified by past investigations as important. However, until now a data set has not been available to allow for geographical and seasonal stratification.

The main purpose of this study is to further investigate those relevant radar detectable signatures, e.g., maximum effective radar reflectivity factor, echo top height, and the structure of individual severe storms as identified by previous studies by Browning and Ludlam (1962), Browning and Donaldson (1963), Browning (1964), and Marwitz (1972a,b,c). The primary emphasis will be placed on a determination of those signatures which most successfully predict occurrences of severe weather. This will enable the operational forecaster to more objectively determine the probable nature of a radar-observed thunderstorm, thus aiding him in his responsibility of issuing severe weather warnings.

To substantiate this study, the known structure of typical severe storms, especially those of the Great Plains, will be discussed. In addition, the effect of

environmental winds on the occurrence of severe thunderstorms will be elucidated. Throughout this study a more thorough understanding of the relationships between severe storm occurrences and radar detectable signatures can be realized in terms of different geographic locations and season. Such understanding should have a positive impact in providing additional help to the severe weather forecaster.

CHAPTER II

DATA

The sources of data used in this study include:

1) United States Air Force Air Weather Service (USAF/AWS) detachments throughout the U. S. for the radar data and some environmental data.

2) Operating Location (OL) -A, United States Air Force Environmental Technical Applications Center (USAF/ETAC) for the rawinsonde data.

3) The National Severe Storms Forecast Center (NSSFC) for the verification data.

In the following, each of these data sets is detailed.

a. Radar Data

A new data source has been made available to the meteorological community to define radar detectable signatures associated with severe thunderstorms. These radar data were gathered by AWS units from April 1975 to July 1977, using AN/FPS-77 radars in the U. S. The AN/FPS-77 is a 5.35-cm radar with a 1.6 degree half-power beamwidth and a pulse length of 2 μsec. Observations are available for the Great Plains, the High Plains, the Gulf States, the Ohio Valley, the Middle Atlantic, the South, and the West. Data were gathered on an irregular basis by volunteer stations whenever severe weather was likely and when minimum criteria, as specified below,

were met. Data were collected as operational workloads permitted, so in some instances the data were incomplete. Those stations participating in this study are identified in Table 1. Radars used were calibrated by AWS technicians to insure accuracy of measurements and daily operational checks were performed to insure data consistency.

Minimum criteria were established for collection of data. If any or all of the following criteria were met or exceeded, observations were taken and recorded for subsequent analysis.

1) The equivalent radar reflectivity factor (Z_e) is at least 30 dBz.

2) The thunderstorm top is at least 40,000 ft in the summer, or is within 5,000 ft of the tropopause.

3) If persistent severe storm signatures, such as those summarized by Whiton (1971), are observed.

Radar observations of selected storms were taken at 15 minute intervals, or as close as practicable to that interval. Observations were initiated when cells approached within 60 nm of the radar. Observations included the following information:

1) Time of the observation to the nearest minute.

2) Value of the maximum equivalent radar reflectivity factor (Z_e max).

3) Height of Z_e max.

TABLE 1

LIST OF PARTICIPATING STATIONS

BY GEOGRAPHIC REGION

Station	Geographic Region	Location
	Great Plains	
Cannon AFB, NM		3423N 10319W
Fort Riley, Ks		3903N 9646W
Reese AFB, Tx		3326N 10203W
Vance AFB, Ok		3620N 9754W
	Gulf Coast	
Keesler AFB, Ms		3024N 8855W
Randolph AFB, Tx		2932N 9817W
	South	
Columbus AFB, Ms		3339N 8827W
Craig AFB, Al		3221N 8659W
Fort Benning, Ga		3220N 8500W
Moody AFB, Ga		3058N 8312W
	West	
Davis-Monthan AFB, Az		3210N 11053W
Mountain Home AFB, Id		4303N 11552W
	Middle Atlantic	
Seymour-Johnson AFB, NC		3520N 7758W
	Ohio Valley	
Fort Campbell, Ky		3640N 8729W
	High Plains	
Minot AFB, ND		4825N 10120W

4) Azimuth and range of Z_e max from the radar.

5) Maximum echo top height.

6) Height of the echo top when radar gain is reduced by 30 dBz (30 dBz top).

7) Any subjective remarks considered pertinent to the storm.

8) 1976 and 1977 data also included the value of the equivalent radar reflectivity factor at 10,000 ft.

Data available consisted of 96 cases containing 408 radar observations over the regions of the U. S. previously identified. Of these data, 7 cases containing 11 observations were discarded due to the quality or incompleteness of the observations, and 20 cases with 100 observations were discarded due to lack of verification data. The data set analyzed in this study consisted of 69 cases containing 297 radar observations. The data covered the period from April 1975 to June 1976 in the area of the U. S. east of 105° west longitude. Of these data, 28 cases containing 124 observations were from the Great Plains and 11 cases with 56 observations were from the South. The remaining data were distributed among the remaining geographical regions noted previously.

b. <u>Environmental Data</u>

Participating AWS units supplied environmental wind data by using facsimile charts available over NAFAX/NAMFAX circuits. Environmental wind fields were

determined by using the Winds Aloft charts (ULUS 1 and ULUS 2) for the 5,000, 10,000, 14,000, 20,000, 25,000, 30,000, and 35,000 ft levels to define the vertical structure of the field. Freezing level data were determined by using the applicable Composite Moisture chart (AOUS 1). Tropopause data were determined from applicable and representative rawinsonde data received locally.

Environmental soundings were obtained from OL-A USAF/ETAC for those cases which were associated with severe weather. Soundings were obtained from release stations upstream of the occurrence and for release times prior to occurrence of the severe event in order to estimate the nature of the thunderstorm's environment. This data set includes atmospheric temperatures and dew point depressions at standard and intervening levels. These data were then used to identify levels that had superadiabatic lapse rates. Further, wind data are recorded at 1 minute intervals during the ascent, along with the height (MSL) of the data level in feet and the height (AGL) in meters. Although not proximity soundings, these data offer insights into the environment which spawned the severe thunderstorm.

c. Verification Data

Severe weather events are defined as the occurrence of hail three-quarter inch or larger, surface

winds 50 knots or stronger, or a tornado or a funnel cloud. The NSSFC Severe Environmental Local Storm (SELS) log from 1 January 1975 to 30 June 1976 was used to verify severe weather events. This log is a record of severe weather events in the U. S. and gives the time of the reported occurrence, its location by latitude and longitude, its character (hail, damaging wind, tornado), and gives hail size or maximum wind gusts when available and applicable.

CHAPTER III

METHODOLOGY

This study involves not only the identification of conventional radar detectable signatures for severe storm determination, but also considers the structure and development of the storm.

a. Thunderstorm Structure

Browning and Ludlam (1962) studied a severe thunderstorm in England which maintained itself for several hours, attaining a quasi-steady state, in sharp contrast to the rapidly developing and dissipating nature of the thunderstorms studied by Byers and Braham (1949). Radar reflectivities in the area surrounding the central updraft were very high, caused by large concentrations of liquid and frozen hydrometeors. Internal structures such as the "echo-free vault", an "overhang echo", and a "wall" were cited as radar signatures associated with severe thunderstorms. All of these signatures are indicative of the strength and organization of the central updraft. Subsequent studies by Browning and Donaldson (1963) and Browning (1964, 1965) confirmed the existence of similar signatures in severe thunderstorms in Oklahoma.

Several categories of severe thunderstorms have been proposed. Browning (1964) termed a "supercell" severe thunderstorm as a single cell storm which propagates

to the right of the mean environmental wind during its quasi-steady, mature stage. Marwitz (1972a,b,c) also listed "multicells" and "severely sheared" supercell storms as categorical entities of severe storms. However, Lemon (1977a,b) theorized that different categories of severe storms are but stages of a continuous process of thunderstorm evolution, where the stages of evolution are directly related to the strength and organization of the central updraft. According to Lemon, the severe storm begins as a non-severe multicell storm. Under the influence of an organized vertical motion field due to local zones of convergence, this non-severe storm may develop into a severe multicell storm. At this stage the central updraft is strong enough to create a "weak echo region" (WER, see Browning and Ludlam, 1962). Surface weather is characterized by hail 2 cm or larger, but with winds generally less than 50 knots. The storm may develop into a supercell if sufficient energy exists and the strength and organization of the central updraft adequately increases. The WER now forms a "vault" (Browning and Ludlam, 1962; Browning and Donaldson, 1963; Marwitz and Berry, 1970) or a "bounded weak echo region" (BWER, see Chisholm, 1973). Hail 4.5 cm or larger and surface winds greater than 50 knots are likely surface phenomena at this stage. Also, the signature of the tornado cyclone (Brooks, 1949), the hook or pendant,

may appear on radar, with tornadic activity a possibility.

The dissipation of severe thunderstorms often results in the occurrence of the largest hail and tornadic activity. During the dissipating stage the radar "hook echo" spirals inward and "wraps up" (Lemon, 1977a) as the central updraft becomes disorganized. The surface weather abates as the severe storm once again reverts to its non-severe state.

The environment of a thunderstorm is indicative of the nature of the mature thunderstorm and will dictate whether the storm may become severe. Mahrt (1977) found that a shallow, moist layer in the lowest layers of the atmosphere is more likely to produce severe storms than a deep, moist layer. The shallow layer allows only organized vertical motion fields to form, while the deeper layer allows disorganized cumulus activity. Also, a wind field in which the wind direction veers with height and has sufficient vertical shear is more likely to generate severe thunderstorms than one with little of either (Miller, 1972). Marwitz (1972c) suggested that supercells continue to develop under the action of extreme shear to become "severely sheared" storms.

In many instances the WER, the vault, or other internal signatures of a severe storm are masked by intervening precipitation, especially at the shorter wavelengths (see Appendix B). Therefore the reflectivity

maximum of the storm, its vertical extent, and other radar detectable signatures are used to infer the strength and organization of the central updraft. Donaldson (personal communication) suggested that the height of the maximum reflectivity above the freezing level be used as a parameter to identify those thunderstorms capable of producing severe weather. In this study a new parameter is introduced, the 30 dBz height. This signature is obtained by using the radar at a reduced gain in order to locate those areas of greatest reflectivity within the thunderstorm. The vertical extent of this signature then identifies the vertical extent to which large particles or large concentrations of particles are carried by the central updraft, an indication of its strength.

b. Data Analysis and Verification

The determination of radar parameters which indicate the severe weather potential of a thunderstorm is an exercise of empirically matching radar observations and verified occurrences of severe weather. Sal'man and Gashina (1974) stated that once radar parameters are determined for identification of severe thunderstorms in a given study, the results of that study may only be applicable to thunderstorms occurring in the geographic area where the study was conducted. This investigation seeks to define signatures indicative of severe weather over several geographically different regions of the

United States.

The radar data supplied by AWS units are grouped according to geographic regions which have similar large-scale characteristics. The regions chosen closely follow those defined by Pautz and Doloresco (1963) and Galway (1977), depicted in Figure 1. This allows a larger data base to be established with only minor losses due to geographic differences. These data are then compared with reported occurrences of severe weather events as identified by the NSSFC SELS log. A thunderstorm is verified

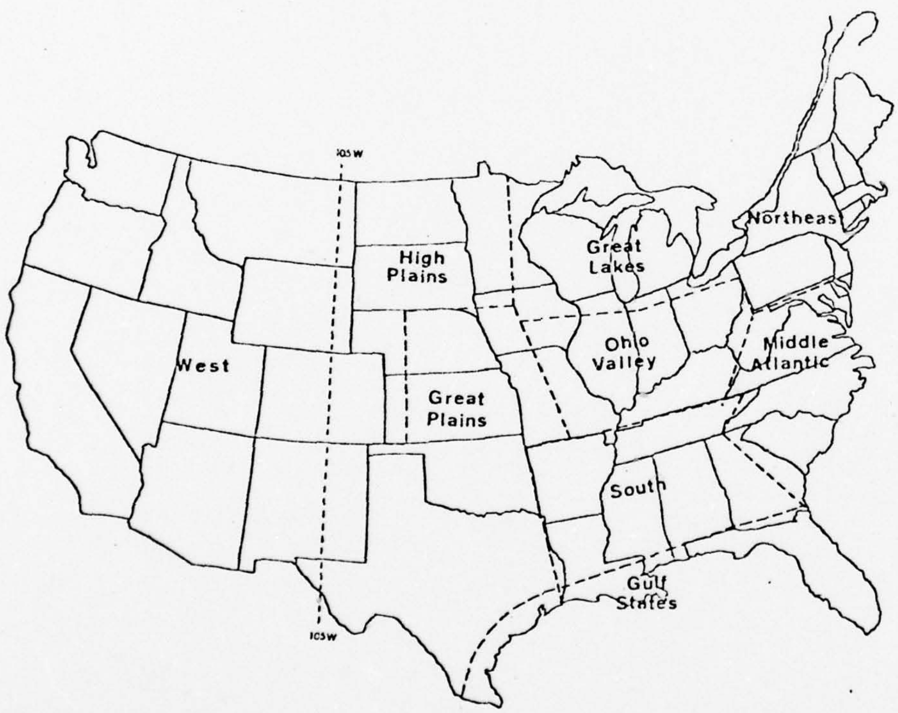

Figure 1. Geographical regions used for separation of data. Regions follow the work of Pautz and Doloresco (1963) and Galway (1977).

as a severe storm only when the following criteria are met: 1) the severe event associated with the storm must be reported within 60 nm of the station, and 2) the event must occur within 30 minutes of a radar observation. Any storm detected by radar which does not meet these criteria is judged to be non-severe.

Radar data are also plotted on time sections to visually depict the motion, growth, and decay of the storm. Occurrences of severe events are also plotted so that comparisons may be made between variations in radar parameters and severe weather occurrences. Determination of storm speed is based on times of consecutive observations and the positions of Z_e max. Figure 2 is a time section of the severe thunderstorm which occurred near Reese AFB, Texas on 21 May 1976. Tropopause and freezing level data were supplied by the participating units.

Radar signatures associated with severe thunderstorms from previous studies are screened and the results of Donaldson et al. (1975b) are used to select those signatures deemed worthwhile to investigate. These signatures include echo tops of thunderstorms, penetrations of the tropopause by thunderstorms, the value of Z_e max, and the height of Z_e max. Also, the new radar parameter previously introduced, the 30 dBz height, will be scrutinized.

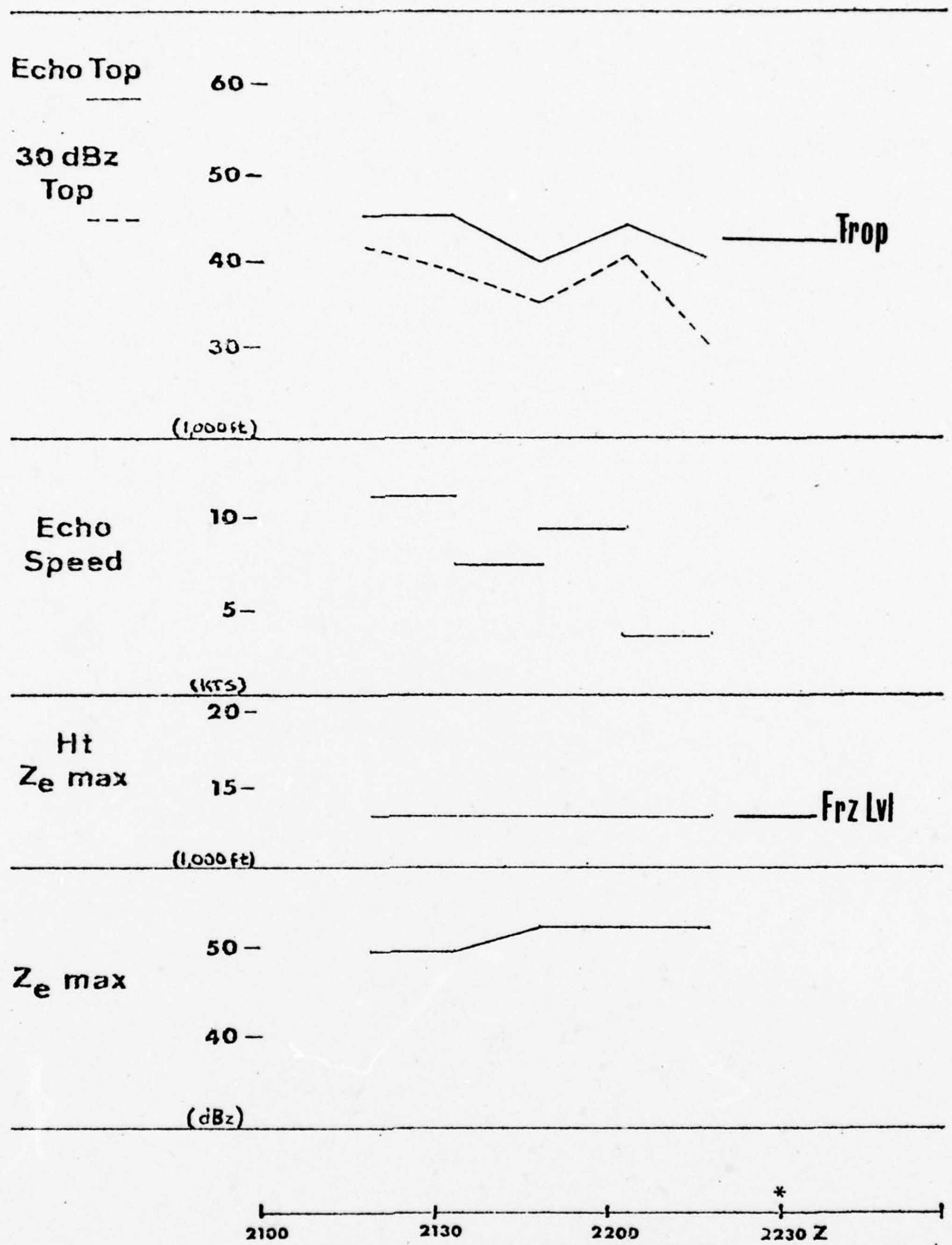

Figure 2. Time section analysis of radar observations of a severe thunderstorm near Reese AFB, Texas on 21 May 1976. Occurrence of severe weather event is denoted by*.

These parameters are screened and their reliability in correctly identifying severe thunderstorms is determined by using the critical success indicator (CSI) developed by Donaldson et al. (1975a), following the concepts of Dennis et al. (1971). This method of determining those parameters relevant to severe storm identification or prediction takes into account both errors of non-prediction (misses) and errors of issuing false alarms ("crying wolf").

The radar data are analyzed against verification data in four distinct categories. The first category includes radar detectable signatures that correctly identified or predicted a severe weather event and are denoted by "x". In this investigation, those cases which met the previously-specified criteria of spatial and temporal resolution are included in this set. The second category consists of those instances where the signature identified or predicted the storm to be non-severe but severe weather occurred (miss) is denoted by "y". In this investigation a miss is indicative of a parameter which requires further sampling because no warning is ever issued, an unacceptable situation.

Thirdly, those cases where the signatures identified or predicted a severe storm but a non-severe or no severe storm occurred is denoted by "z". In this instance the forecaster issued a warning and no severe storms occurred

to support his warning. This method of "crying wolf" decreases the credibility of the warnings and is dangerous since future warnings may be ignored by the customer.

Finally, those storms correctly identified as non-severe are denoted by "w". These categories may be conveniently summarized in matrix form, as shown in Figure 3, with the prediction based on the parameter across the top and verification of severe storm occurrence on the left.

Next, the values in the various categories are used to determine several important indicators of the reliability of the chosen parameter as a tool for defining severe thunderstorms. The first such indicator is the probability of detection (POD), defined as the proportion of severe weather events correctly identified by the chosen parameter, and given by:

$$POD = \frac{x}{x + y} \tag{1}$$

		PREDICTED	
		SEVERE	NON-SEVERE
OBSERVED	SEVERE	x	y
	NON-SEVERE	z	w

Figure 3. Critical success indicator matrix (after Donaldson, 1975a).

This value should be high for any chosen parameter, 1.0 indicative of a perfect parameter, one which correctly identifies every occurrence of severe thunderstorms.

If a chosen parameter incorrectly predicts a storm to be severe, then the forecaster has issued a false alarm. The ratio of incorrect predictions of a severe event is known as the false-alarm ratio, given by:

$$\mathrm{FAR} = \frac{z}{x + z} \tag{2}$$

The value for FAR should be small for any chosen parameter, with 0.0 indicative of a parameter which correctly identifies every occurrence of a severe event ($z = 0$).

The critical success indicator (CSI) reflects the merit of a chosen parameter in correctly identifying those thunderstorms associated with severe weather. The CSI is defined as the ratio of successful predictions to the sum of successful prediction, misses, and false alarms, and is given by:

$$\mathrm{CSI} = \frac{x}{x + y + z} \tag{3}$$

The value of CSI should be large for any chosen parameter, 1.0 indicative of a parameter which correctly identifies every thunderstorm associated with severe weather.

Dennis et al. (1971) and Sal'man and Gashina

(1974) observed that combinations of radar parameters are more likely to correctly identify those thunderstorms capable of producing severe weather. Therefore, several experiments are conducted by using combined single radar parameters to yield a new radar parameter. This new parameter is then tested for merit by using the CSI method.

In order to further stratify the data, seasonal separation is attempted whenever the amount of data warrants such an approach. The stratification results in a data set for spring (March, April, May) and one for summer (June, July, August) for the Great Plains area.

For those cases where a severe thunderstorm is identified, rawinsonde data are analyzed for stations upstream in time and space from the location of the occurrence. Vertical wind profiles are plotted by using data received from OL-A USAF/ETAC. The veer and shear of the wind field is calculated from the surface to 35,000 ft. These results are compared to typical flow regimes associated with severe thunderstorms as identified by Marwitz (1972a,b,c). The stability of the atmosphere is determined by using the Total Totals index, while the likelihood for severe thunderstorm occurrence is determined by calculation of the Severe Weather Threat (SWEAT) index of Miller (1972).

CHAPTER IV

DISCUSSION OF RESULTS

This investigation has been hampered by an insufficient number of cases with severe thunderstorm occurrences. Those cases which were verified as severe were carefully analyzed and will be fully discussed. Some geographical differences were noted in the effective parameters for severe storm identification and seasonal variations were noted in the data of observations of Great Plains storms.

a. Severe Thunderstorm Identification and Radar Data Analysis

Thunderstorms observed on radar were designated severe when previously established criteria were met. In several geographic regions no severe thunderstorms were identified and therefore analysis could not be accomplished. In several instances high reflectivity factors were observed, sometimes in conjunction with high echo tops, but no verification of a severe event could be established. For example, reflectivity factors of 59 dBz were found in one Gulf States storm, but the storm was determined to be non-severe. However, the echo top of this storm was 14,000 ft below the tropopause level. This indicates that the central updraft was not strong enough for the storm to produce severe

weather at the surface. Also, in the data from the Ohio Valley there were storms with reflectivity factors up to 66 dBz and whose tops were near the tropopause, but no severe events could be associated with them. Radar observations in the Middle Atlantic and High Plains regions were insufficient to allow any kind of analysis.

Verification of severe weather associated with observed storms in the South and the Great Plains was more successful, although marginally so. One severe thunderstorm was identified in the South, near Moody AFB, Ga. Radar observations showed that the Z_e max of this storm was 56 to 58 dBz, the echo top was 10,000 ft above the tropopause, and the height of Z_e max was 9,000 ft above the environmental freezing level. This combination of radar information indicates a well-developed central updraft region in the storm, a very strong indicator of a potentially severe storm.

The verification results in the Great Plains revealed that out of 28 thunderstorms observed, 7 were severe. Two cases occurred in the summer, while the remaining cases occurred in the spring. Generally, higher reflectivities were found in spring storms, but this result may reflect the small data base used. Echo tops associated with severe thunderstorms varied widely. The lowest top associated with a severe storm (36,000 ft) was observed during the spring in Texas. The highest

top (51,000 ft) associated with a severe storm was observed during late summer in Kansas.

Analysis of radar observations for several geographic regions revealed disparities in the structure of radar-observed thunderstorms. The average height of Z_e max was found to be 13,000 ft in the southern regions (South and Gulf States), 11,800 ft in the Great Plains, and about 10,000 ft in the High Plains. These differences may be attributed to variations in the height of the average freezing level and the height of the tropopause as one moves poleward from the Gulf of Mexico. That the height of hail-producing thunderstorms decreases as one moves poleward has been summarized by Whiton and Hamilton (1976).

The average Z_e max was 54 dBz for thunderstorms in the South, while the average for the Great Plains was 51 dBz. The average value for Great Plains severe thunderstorms 53 dBz. A similar determination could not be made for the South because of insufficient data.

Following a suggestion by Donaldson (personal communication), the height of Z_e max was compared to the height of the freezing level as a possible identifier of severe thunderstorms. Results for all storms showed that the height of Z_e max was greater than the height of the freezing level in every instance. However, due to the small number of cases available, no relationship

could be established between the height differences and the severity of the surface phenomenon.

Seasonal variations were found in the average heights of thunderstorms of the Great Plains in this investigation. The average height of observed storms was 44,300 ft, with 43,600 ft being the average height of spring storms and 45,200 ft the average height of summer storms. For the severe storms, the average overall height rose to 45,000 ft, with summer storms averaging 49,500 ft. The representativeness of these values are questionable due to the small data sample, but they do indicate that seasonal differences are evident.

Time series analyses of severe storm radar observations revealed that the occurrence of the severe event was preceded by a decrease, sometimes gradual, other times rapid, of the height of the echo top. Further, the height of the 30 dBz top decreased in most cases, in many cases more rapidly than the echo top. The speed of storms varied from 4 to 30 knots during or prior to the occurrence of severe weather. The magnitude of Z_e max likewise varied, but in most instances increased prior to the occurrence of severe weather. Taken in the context of Lemon's (1977a,b) concept of thunderstorm structure and development, these signatures represent the decay of the severe storm. The stage of the severe storm would be difficult to assess, but based

on the severe surface phenomena observed and the remarks of the radar operator, several of the observed thunderstorms could be of the supercell variety. Analysis of the Union City storm by Lemon, Burgess, and Brown (1978) revealed that the echo top collapse was associated with the collapse of the vertical motion field (BWER collapse), followed rapidly by the occurrence of a severe event. Thus, a significant decrease of the height of an echo top, that deemed sufficient for severe weather initiation (above or near the tropopause) may be an important thunderstorm characteristic to monitor in order to determine the time of occurrence of the severe event. Lemon, Burgess, and Brown (1978, see their Figure 13) point out that not every echo top decrease indicates thunderstorm collapse, nor that every collapse leads to a severe event. However, the results of this study support the concept that a severe event is preceded by a decrease of the echo top height of the storm, probably associated with a weakening of the central updraft core. Time section analyses of all severe storm cases are given in Figure 2 and Figures 4 through 10.

b. Radar Parameters for Severe Storm Identification

The capability and the reliability of a radar parameter to correctly identify severe thunderstorms may be measured using the critical success indicator (CSI) of Donaldson et al. (1975a). A very reliable

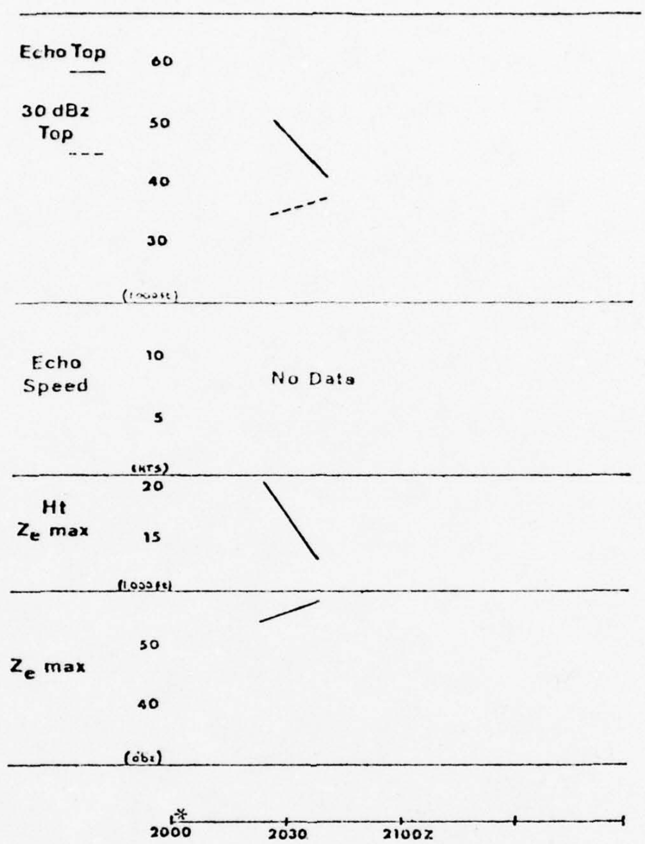

Figure 4. Time section analysis of radar observations for Moody AFB, Ga. for 11 May 1976. Severe event is denoted by *.

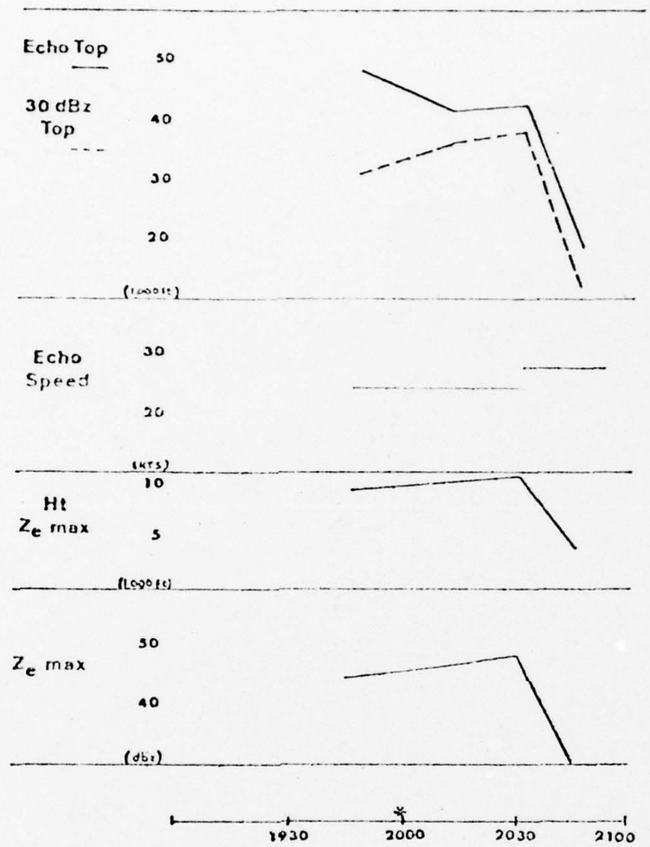

Figure 5. Time section analysis of radar observations for Fort Riley, Ks. for 24 June 1975. Severe event is denoted by *.

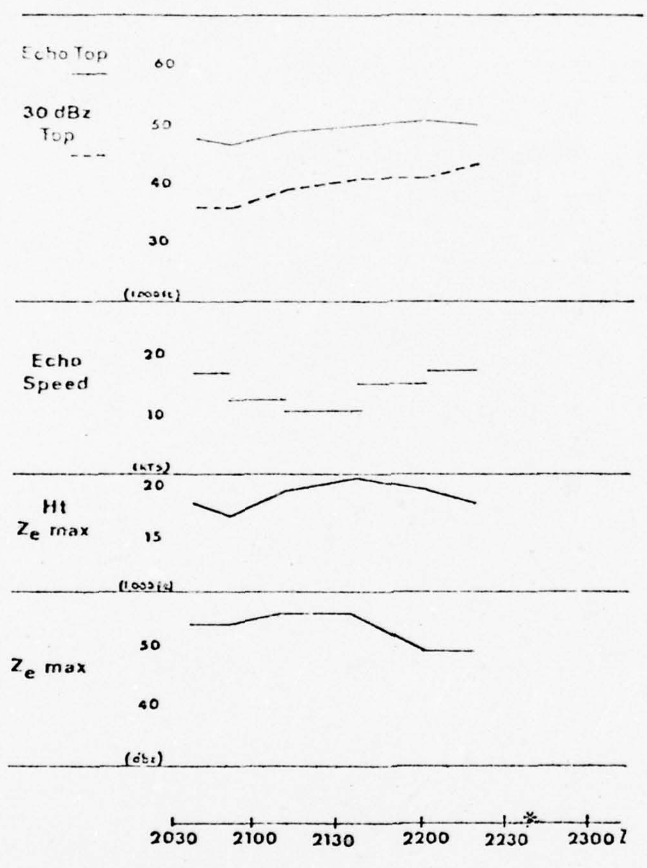

Figure 6. Time section analysis of radar observations for Fort Riley, Ks. for 4 September 1975. Severe event is denoted by *.

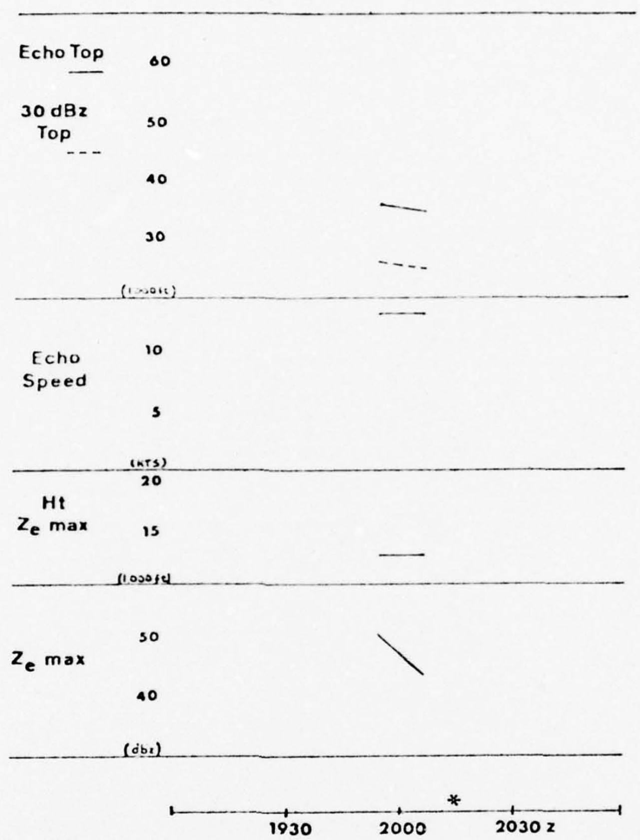

Figure 7. Time section analysis of radar observations for Reese AFB, Tx. for 28 April 1976. Severe event is denoted by *.

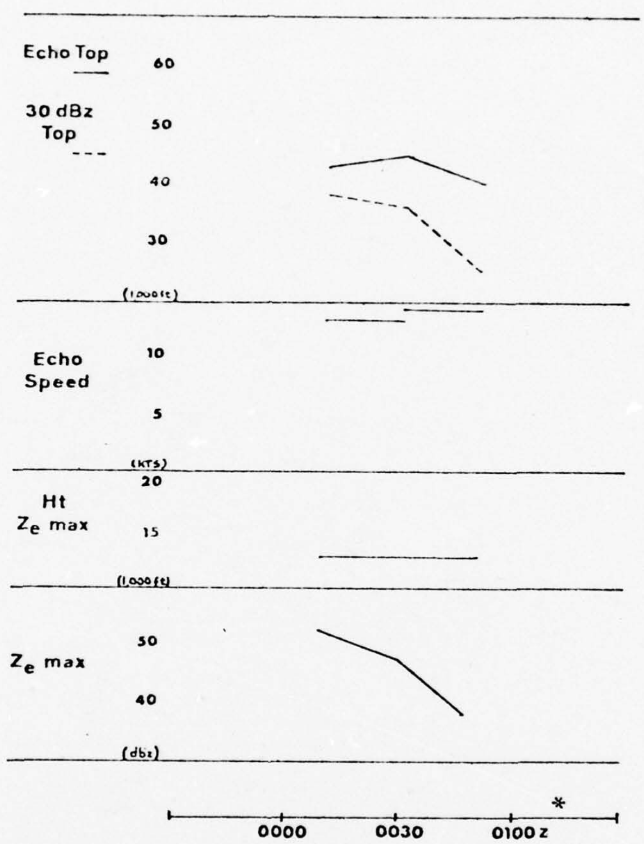

Figure 8. Time section analysis of radar observations for storm 1, Reese AFB, Tx. for 23 April 1976. Severe event is denoted by *.

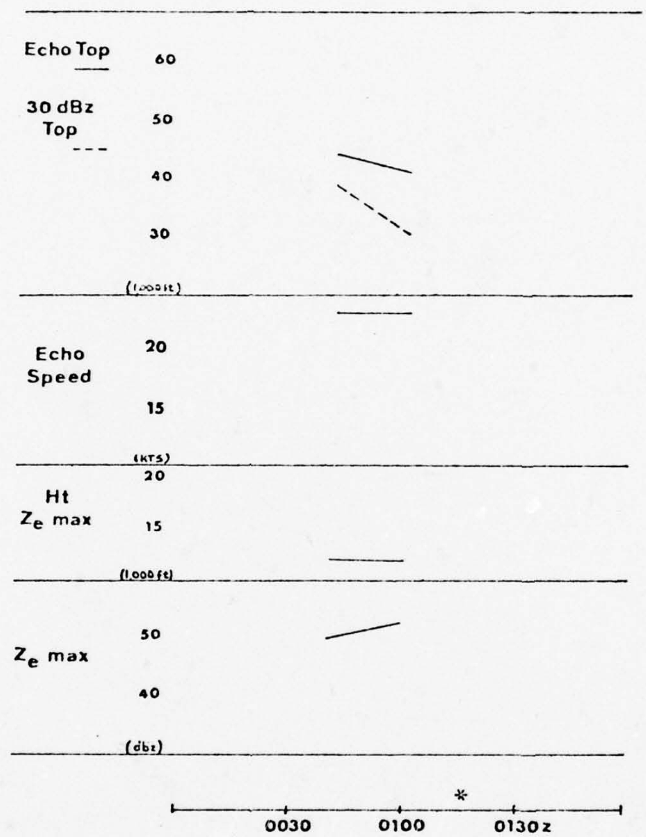

Figure 9. Time section analysis of radar observations for storm 2, Reese AFB, Tx. for 23 April 1976. Severe event is denoted by *.

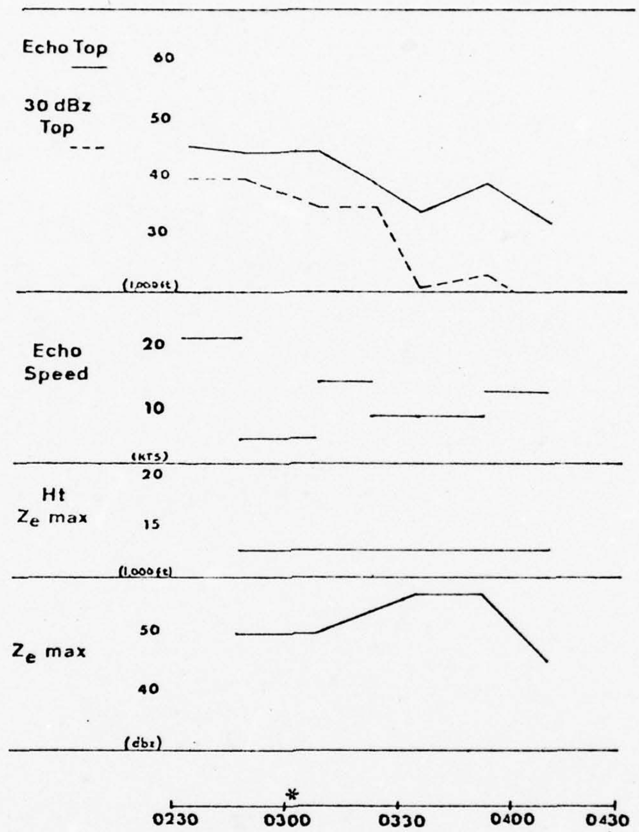

Figure 10. Time section analysis of radar observations for Reese AFB, Tx. for 25 May 1976. Severe event is denoted by *.

parameter would have a POD of over .50, a FAR of less than .50, and a CSI of .33 or above. These are realistic goals, but few conventional radar parameters meet or exceed these goals (see Donaldson et al., 1975b).

Results of analyses to determine the ability of the radar parameters to correctly identify severe thunderstorms are given in Tables 2 to 5. Seasonal stratification of data was accomplished for the Great Plains, but data in the South were insufficient for such treatment. Due to the small data sample, numerical values of CSI, POD, and FAR may be misleading, but the rank ordering allows interpretation of the relative merits of the parameters considered. The numerical values seem especially unrepresentative in cases where POD equals 1.0 or the FAR equals 0.0. A larger data base, with many more verifications would most certainly change the numerical values of the CSI, POD, and FAR, but the rank order of the parameters may not change as drastically.

The first striking feature noted in the tables is the reliability of the 30 dBz height in identifying severe storms. In every instance, especially when this parameter is considered together with the echo top height or the height of the tropopause, it ranks very high on the list. The reason for such reliability is understandable since a large 30 dBz height indicates a strong central updraft. The 30 dBz height considered by itself is not

TABLE 2

RANK ORDERING OF PARAMETERS' ABILITY TO IDENTIFY SEVERE STORMS IN THE GREAT PLAINS FOR SPRING AND SUMMER

Parameter	CSI	POD	FAR
30 dBz top within 5,000 ft of the echo top	.56	.71	.29
3 km $Z_e \geq$ dBz	.45	1.0	.55
30 dBz top within 5,000 ft of the echo top and top penetrating the tropopause	.44	.57	.33
30 dBz height $\geq$ 40,000 ft	.43	.43	0.0
Z_e max $\geq$ 51 dBz and 30 dBz height $\geq$ 35,000 ft	.42	.71	.50
30 dBz height $\geq$ 35,000 ft	.40	.86	.57
30 dBz height within 5,000 ft of the tropopause	.40	.57	.43
30 dBz height within 10,000 ft of the echo top	.40	.86	.57
3 km $Z_e \geq$ 45 dBz	.38	1.0	.62
30 dBz top within 10,000 ft of the tropopause	.38	.86	.60
3 km $Z_e \geq$ 40 dBz	.36	1.0	.64
30 dBz height $\geq$ 25,000 ft	.33	1.0	.67
Z_e max $\geq$ 45 dBz and top penetrating the tropopause	.33	.86	.62
Echo top penetrating the tropopause	.31	.71	.64
3 km $Z_e \geq$ 50 dBz	.30	.80	.87
30 dBz height $\geq$ 30,000 ft	.30	.86	.68

Parameter	CSI	POD	FAR
Z_e max $\geq$ 48 dBz	.30	1.0	.70
Echo top $\geq$ 35,000 ft	.29	1.0	.71
Z_e max $\geq$ 45 dBz	.29	1.0	.71
Z_e max $\geq$ 51 dBz	.29	.71	.66
Z_e max $\geq$ 42 dBz	.28	1.0	.72
Z_e max $\geq$ 50 dBz and echo top $\geq$ 44,000 ft	.27	.43	.57
Echo top $\geq$ 45,000 ft	.27	.57	.67
Z_e max $\geq$ 45 dBz and echo top $\geq$ 45,000 ft	.27	.57	.67
Echo top $\geq$ 40,000 ft	.26	.85	.72
3 km $Z_e \geq$ 54 dBz	.17	.20	.50
Z_e max $\geq$ 54 dBz	.15	.29	.75
Echo top $\geq$ 50,000 ft	.14	.13	.67

TABLE 3

RANK ORDERING OF PARAMETERS' ABILITY TO IDENTIFY SEVERE STORMS IN THE GREAT PLAINS FOR SPRING

Parameter	CSI	POD	FAR
30 dBz top within 5,000 ft of the echo top	.57	.60	.33
30 dBz top within 5,000 ft of the tropopause	.57	.80	.33
30 dBz height $\geq$ 35,000 ft	.50	.80	.43
Z_e max $\geq$ 51 dBz and 30 dBz height $\geq$ 35,000 ft	.50	.80	.43
3 km $Z_e \geq$ 48 dBz	.45	1.0	.55
30 dBz height $\geq$ 25,000 ft	.45	1.0	.55
30 dBz top within 5,000 ft of the echo top and top penetrating the tropopause	.43	.60	.40
3 km $Z_e \geq$ 40 dBz	.42	1.0	.58
3 km $Z_e \geq$ 45 dBz	.42	1.0	.58
30 dBz height $\geq$ 40,000 ft	.40	.40	0.0
30 dBz top within 10,000 ft of the echo top	.40	.80	.56
Echo top $\geq$ 35,000 ft	.38	1.0	.62
Z_e max $\geq$ 45 dBz	.36	1.0	.64
30 dBz height $\geq$ 30,000 ft	.36	.80	.60
Z_e max $\geq$ 48 dBz	.36	1.0	.64
30 dBz top within 10,000 ft of the tropopause	.36	.80	.60
Echo top $\geq$ 40,000 ft	.33	.80	.65
Z_e max $\geq$ 45 dBz and top penetrating the tropopause	.33	.60	.57

Parameter	CSI	POD	FAR
Z_e max $\geq$ 51 dBz	.31	.80	.67
3 km $Z_e \geq$ 50 dBz	.30	.60	.84
Echo top penetrating the tropopause	.30	.60	.63
Echo top $\geq$ 45,000 ft	.29	.40	.50
Z_e max $\geq$ 45 dBz and echo top $\geq$ 45,000 ft	.29	.40	.50
Z_e max $\geq$ 50 dBz and echo top $\geq$ 44,000 ft	.29	.40	.50
3 km $Z_e \geq$ 54 dBz	.17	.20	.50
Z_e max $\geq$ 54 dBz	.10	.20	.83
Echo top $\geq$ 50,000 ft	0.0	0.0	1.0

TABLE 4

RANK ORDERING OF PARAMETERS' ABILITY TO IDENTIFY SEVERE STORMS IN THE GREAT PLAINS FOR SUMMER

Parameter	CSI	POD	FAR
30 dBz height ≥ 40,000 ft	.50	.50	0.0
30 dBz top within 5,000 ft of the echo top	.50	.50	0.0
30 dBz top within 5,000 ft of the echo top and top penetrating the tropopause	.50	.50	0.0
30 dBz top within 5,000 ft of the tropopause	. 0	1.0	.60
30 dBz top within 10,000 ft of the tropopause	.40	1.0	.60
Echo top ≥ 50,000 ft	.33	.50	.50
Z_e max ≥ 54 dBz	.33	.50	.33
Z_e max ≥ 45 dBz and top penetrating the tropopause	.33	1.0	.67
Echo top penetrating the tropopause	.32	1.0	.67
30 dBz height ≥ 35,000 ft	.29	1.0	.71
Echo top ≥ 45,000 ft	.25	1.0	.75
Z_e max ≥ 51 dBz	.25	.50	.67
Z_e max ≥ 51 dBz and 30 dBz height ≥ 35,000 ft	.25	.50	.67
Z_e max ≥ 45 dBz and echo top ≥ 45,000 ft	.25	1.0	.75
Z_e max ≥ 50 dBz and echo top ≥ 44,000 ft	.25	.50	.67
30 dBz height ≥ 30,000 ft	.22	1.0	.78

Parameter	CSI	POD	FAR
Z_e max $\geq$ 48 dBz	.22	1.0	.78
30 dBz height $\geq$ 25,000 ft	.20	1.0	.80
Z_e max $\geq$ 45 dBz	.20	1.0	.80
Echo top $\geq$ 35,000 ft	.18	1.0	.82
Echo top $\geq$ 40,000 ft	.18	1.0	.82
Z_e max $\geq$ 42 dBz	.18	1.0	.82

TABLE 5

RANK ORDERING OF PARAMETERS' ABILITY TO IDENTIFY SEVERE STORMS IN THE SOUTH FOR SPRING AND SUMMER

Parameter	CSI	POD	FAR
Echo top ≥ 50,000 ft	1.0	1.0	0.0
Echo top ≥ 44,000 ft and Z_e max ≥ 50 dBz	1.0	1.0	0.0
30 dBz top ≥ 35,000 ft	.50	1.0	.50
30 dBz top within 5,000 ft of the tropopause	.33	1.0	.67
Echo top ≥ 45,000 ft	.25	1.0	.87
30 dBz top within 10,000 ft of the tropopause	.20	1.0	.75
Echo top penetrating the tropopause	.20	1.0	.80
30 dBz top 30,000 ft	.20	1.0	.80
Z_e max ≥ 57 dBz	.20	1.0	.80
Z_e max ≥ 51 dBz	.17	1.0	.83
Z_e max ≥ 54 dBz	.17	1.0	.83
Echo top ≥ 40,000 ft	.13	1.0	.87
Z_e max ≥ 48 dBz	.09	1.0	.91
Z_e max ≥ 45 dBz	.08	1.0	.92

as good an indicator, though it also ranks quite high. The FAR of 0.0 associated with the 30 dBz height of 40,000 ft or more is not due to insufficient data. It is due to the fact that this height is so great that any storms whose 30 dBz height is equal or greater than it are almost certainly severe.

The probability of detection using the 30 dBz top in the Great Plains falls sharply in the interval from 35,000 to 40,000 ft, as shown in Figures 14-16. The problem which develops here is that the number of misses (severe weather events not forecast) increases. Since this "miss ratio" is merely the difference between a perfect forecast and the probability of detection, it is pointless to compute another variable. However, when such instances arise it is best to be wary of the meaning of the numbers.

According to Donaldson et al. (1975a), the choice of levels of acceptability are determined by other studies, such as cost analysis studies, but the key feature sought in diagrams such as Figures 11-20 is the CSI peak. Based on these criteria, the following threshold values of investigated radar parameters were found to yield the most success in identifying severe thunderstorms in the Great Plains:

1) Z_e max - 48 dBz for both spring and summer.

2) Echo top height - 40,000 ft for spring; 45,000 ft for summer.

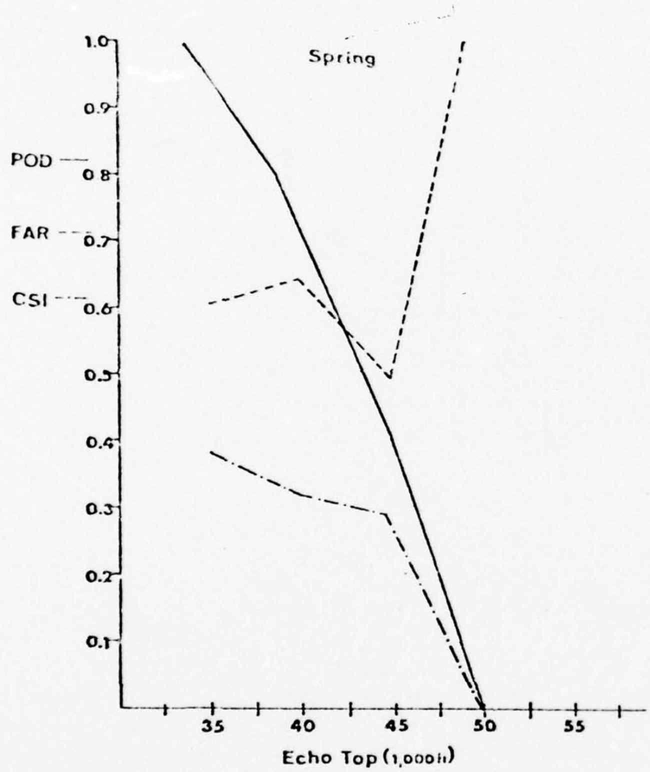

Figure 11. Variation of CSI, POD, and FAR with threshold values of the echo tops for the Great Plains in spring.

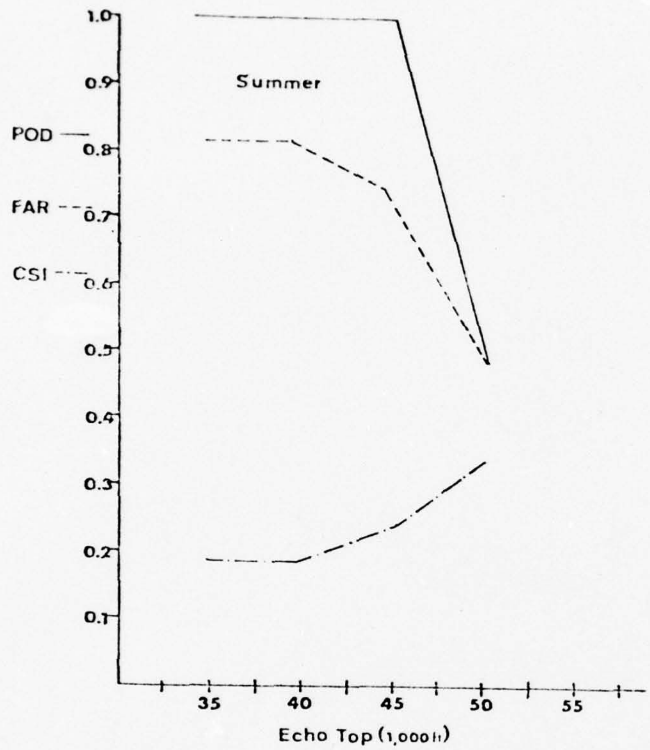

Figure 12. Variation of CSI, POD, and FAR with threshold values of the echo tops for the Great Plains in summer.

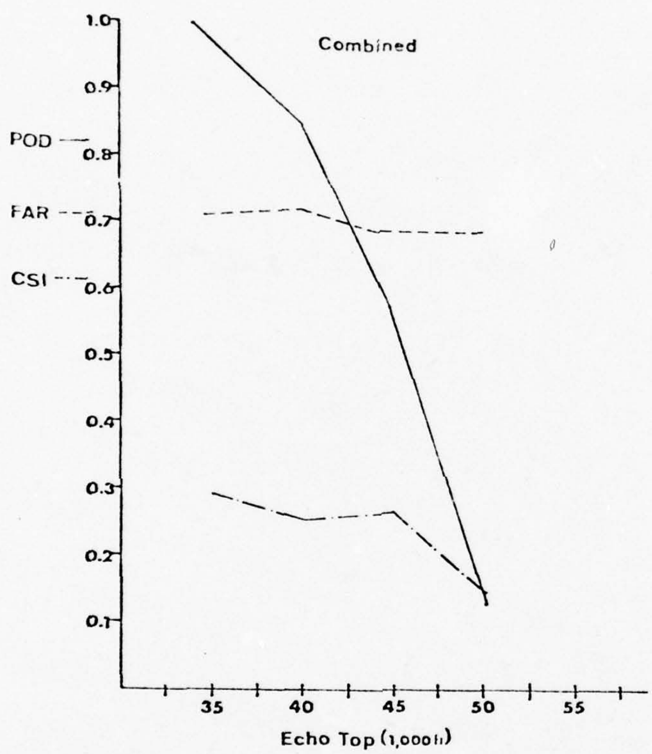

Figure 13. Variation of CSI, POD, and FAR with threshold values of the echo tops for the Great Plains for both spring and summer combined.

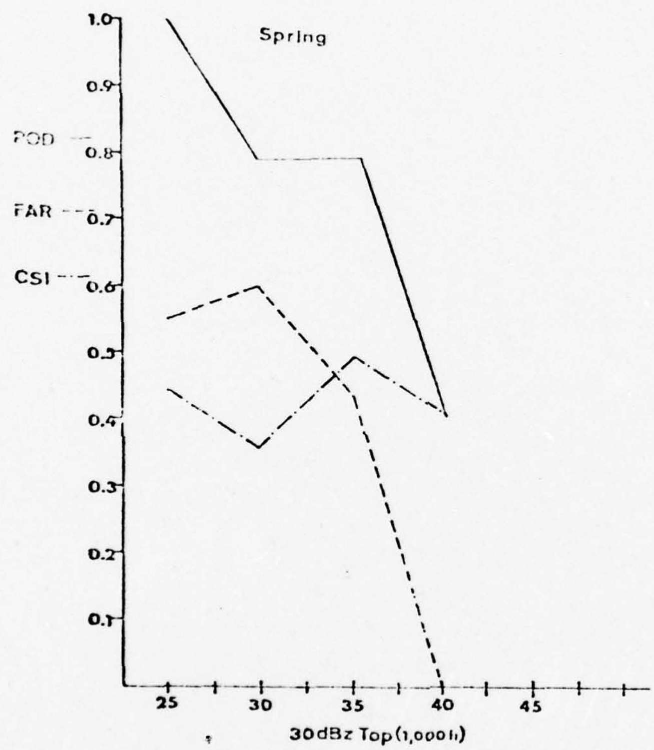

Figure 14. Variation of CSI, POD, and FAR with threshold values of the 30 dBz top for the Great Plains for spring.

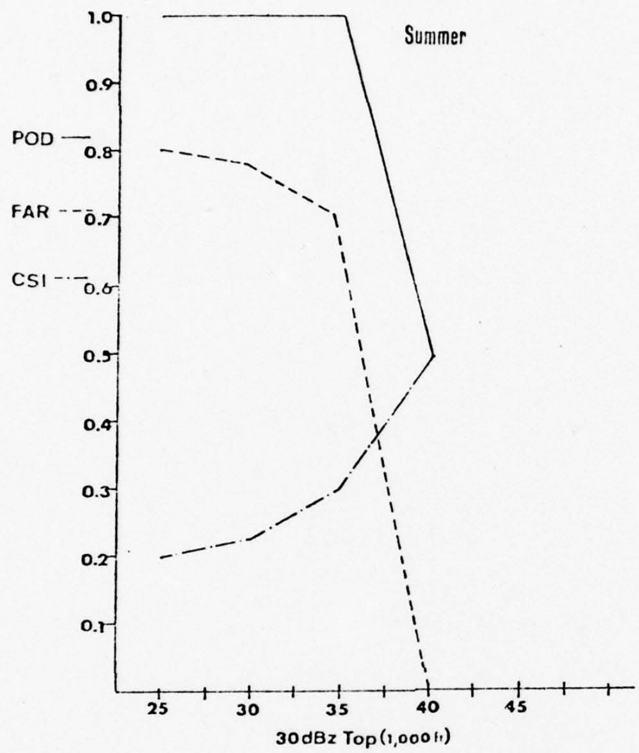

Figure 15. Variation of CSI, POD, and FAR with threshold values of the 30 dBz top for the Great Plains for spring.

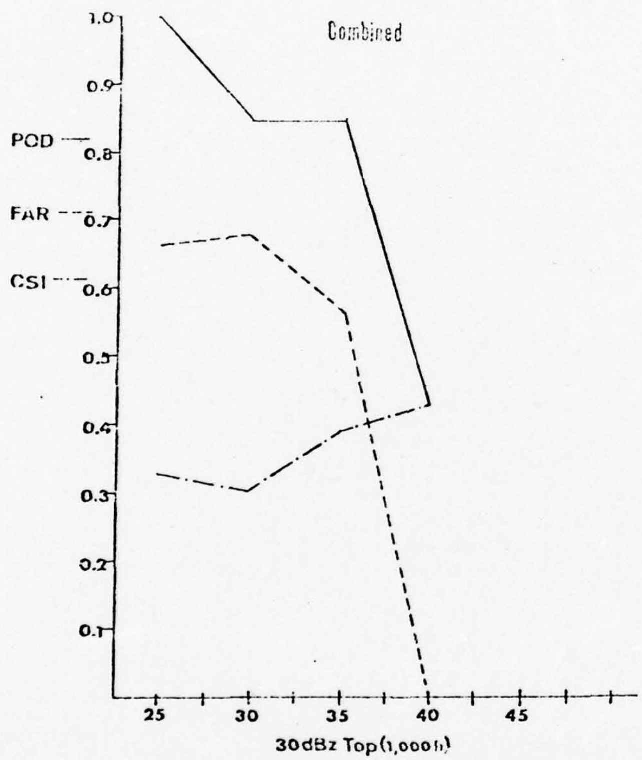

Figure 16. Variation of CSI, POD, and FAR with threshold values for the 30 dBz top for the Great Plains for spring and summer combined.

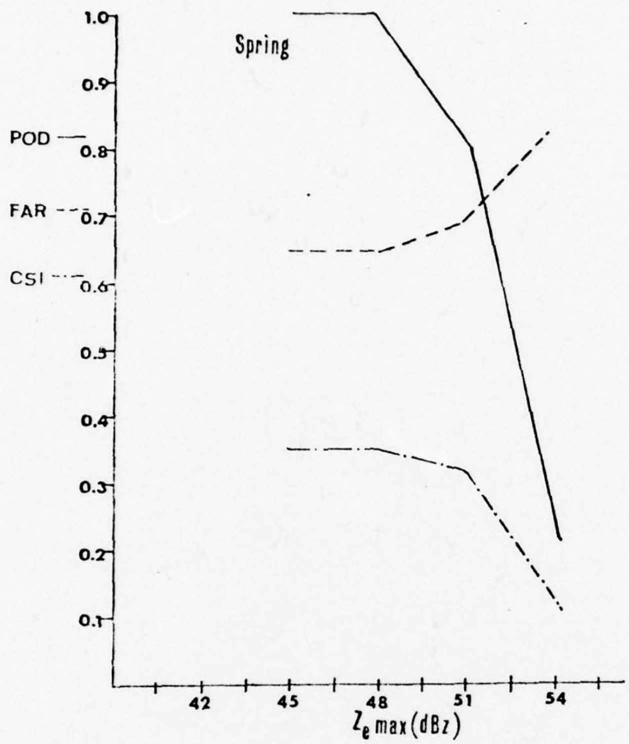

Figure 17. Variation of CSI, POD, and FAR with threshold values for the maximum effective reflectivity factor for the Great Plains for spring.

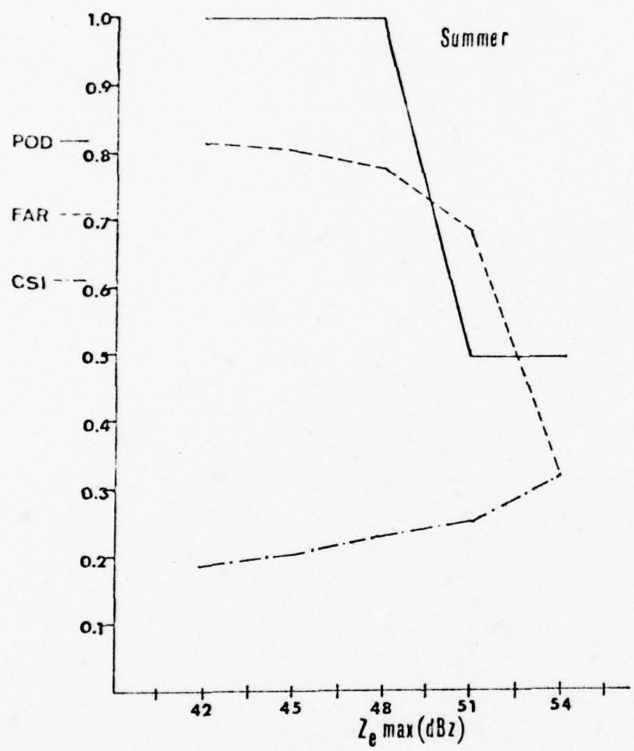

Figure 18. Variation of CSI, POD, and FAR with threshold values for the maximum effective reflectivity factor for the Great Plains in summer.

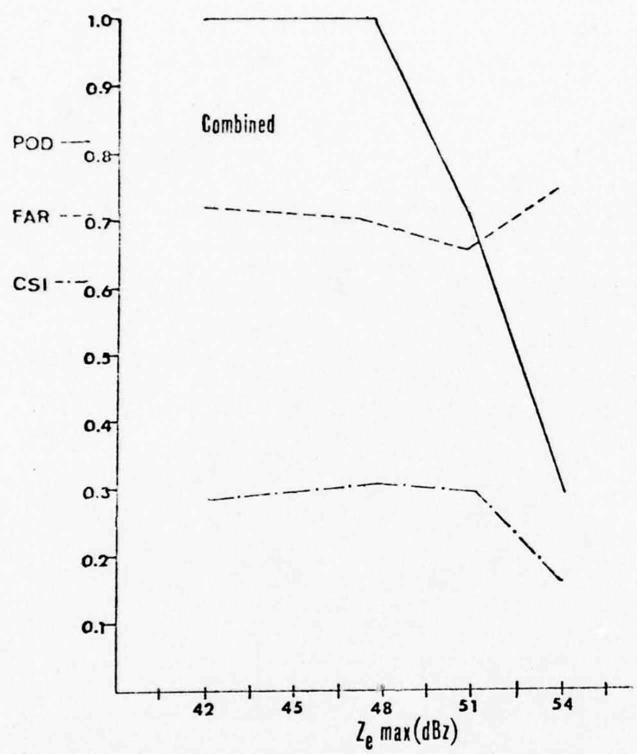

Figure 19. Variation of CSI, POD, and FAR with threshold values for the maximum effective reflectivity factor for the Great Plains in spring and summer.

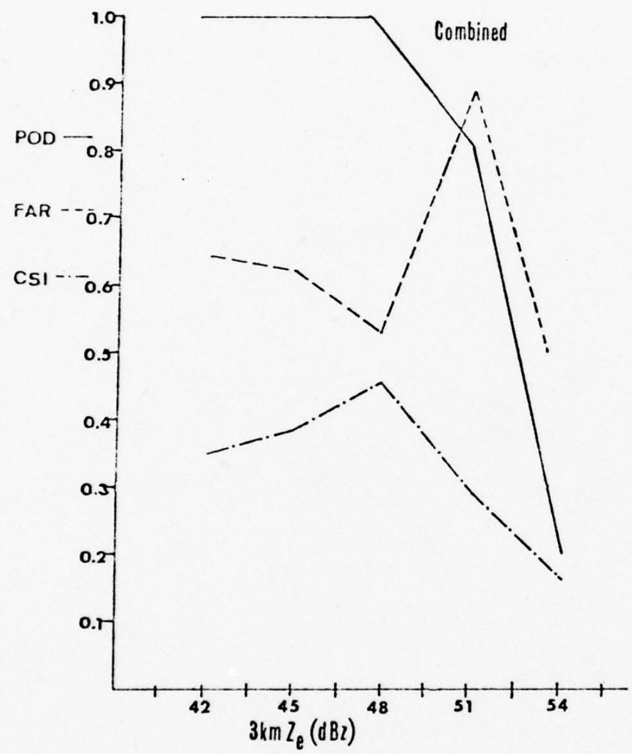

Figure 20. Variation of CSI, POD, and FAR with threshold values of the 3 km effective reflectivity factor for the Great Plains in spring and summer.

3) 3 km (10,000 ft) Z_e - 48 dBz for both seasons.

4) 30 dBz height - 35,000 ft for both seasons. Figures 11 to 20 depict the variation of these diverse parameters as the threshold values change. It is important to recall that these values are suspect due to the small data base from which they were drawn. However, their relative usefulness in severe storm identification, when compared with other values in this study, show that there is still promise in using conventional radar parameters for identifying severe storms.

The rank ordering of parameters to define severe thunderstorms in the South based on only one event was done to compare the relative CSIs and the ordering of these parameters to those in the Great Plains. In general the most successful indicators in the Great Plains also proved to be successful in the South. The 30 dBz height once again proved to be a good parameter for defining severe thunderstorms.

c. Environmental Factors of Severe Storm Occurrence

The environments in which severe storms were determined varied widely. Stability, measured by using the Total Totals index (see Appendix C), varied from 40 to 64 in the cases investigated. The low value is barely sufficient for severe storm development, while the upper value is significantly higher than the threshold value

quoted by Miller (1972) for severe storms. The Severe Weather Threat (SWEAT) index of Miller (see Appendix C) was also used to ascertain the likelihood of severe convective activity. Values for the various cases ranged from 128, well below the threshold for severe storms, to 557, a value much greater than the threshold.

Further, the wind fields prior to onset of the severe event also varied tremendously. Some severe cases were associated with wind fields which backed with height instead of veering, and others were found where negative shear existed.

1) The severe storm which occurred on 11 May 1976 in the South was associated with an environment not generally assumed to be severe weather-producing in the Great Plains. The Total Totals index calculated by using data from the Birmingham (BHM) rawinsonde collected eight hours prior to occurrence of a severe storm was 43 and the SWEAT index was 145. Both values are hardly cause for alarm. The wind field veered with height in the lowest 3 km, with the average direction being 282°. Between 3 and 6 km the winds backed with height, with the average direction being 261°. Generally light shear (3.3×10^{-3} sec^{-1}) was found between 4,000 and 35,000 ft and this value dropped to 2.5×10^{-3} sec^{-1} when the layer from 5,000 to 40,000 ft was considered as the cloud bearing layer. These shear values are below those associated

with severe convective activity in the Great or High Plains (see Marwitz, 1972a,b,c); but the shear may have been sufficient to allow for severe storm development in the South.

Synoptic conditions prior to severe storm initiation were not considered in this study, but a height of 35,000 to 38,000 ft for the 30 dBz level indicates a very well-developed central updraft region, indicative of a very strong vertical motion field. A squall line or a frontal zone could generate sufficient vertical motion to produce such an effect. Tornadoes were associated with this storm and observations indicate that the storm was dissipating after the severe event took place (see Figure 4). Further, the cell was identified by the radar operator as a single cell with a weak-echo region. The conclusion, based on the evidence available, points to a supercell occurrence in this area. Research is lacking on the development of severe storms in this region, but seemingly this convective cell was a very well-developed severe thunderstorm. With the height of Z_e max 9,000 ft above the environmental freezing level, the height difference between the freezing level and the Z_e max level as an indicator of severe storms suggested by Donaldson seems to have been accurate.

Although the structure of severe thunderstorms in the South has never been documented, it is assumed

that the structure of severe storms everywhere is similar. Recall that the structure of the Workingham storm (Browning and Ludlam, 1962) was similar to severe storms in Oklahoma (Browning and Donaldson, 1963, and others). Therefore, the high reflectivities associated with this storm, the environmental wind shear, and the evidence of a reflectivity maximum well above the freezing level leads one to conclude that at least a WER, if not a BWER, was associated with this storm, and this indeed was the case. Further investigations are required in this region to identify severe storm structure.

2) Severe thunderstorm occurrences in the Great Plains varied widely in their environmental settings. In two cases occurring in Kansas during the summer (24 Jun and 4 Sep 1975), the Total Totals were in the mid-40s and SWEAT values were around 150, neither are really severe storm criteria. However, in both instances the rawinsonde data used to calculate these values were over 8 hours old. The atmosphere may have changed significantly in the interim, though release points Topeka (TOP) and Dodge City (DDC) were both upstream from where the severe event occurred. However, the wind patterns for these two cases should not have changed significantly. Weak shear (1.1 to 1.8 x 10^{-3} sec^{-1}) was found in the 24 June case, while negative shear (-1.8 to -2.4 x 10^{-3} sec^{-1}) was found in the 4 September case. Though none

of these environmental indicators would signify severe weather potential, winds greater than 50 knots were reported with the 24 June storm, while gusts to 57 knots were associated with the 4 September storm.

Radar observations reveal that in both instances the storm top was decreasing prior to the severe weather occurrence, but that the 30 dBz top was increasing during this period. This leads to a paradox, in that the central updraft is still carrying sufficient moisture aloft to show an increase in the height of the 30 dBz echo while the echo top indicates that the storm may be dissipating. The paradox may be resolved, however, by noting that shortly after the occurrence of severe weather the entire storm collapses (see Figure 5). In the 4 September case (see Figure 6) the observations indicate that the storm is quasi-steady in its vertical structure prior to the severe event. In both instances, the storms were denoted as single cells with weak-echo regions by the radar operator.

3) Severe thunderstorms occurring in west Texas were found to have been more predictable than the other regions. Total Totals of 58 at Midland (MAF) and 60 at Amarillo (AMA) also more than 8 hours prior to severe thunderstorm occurrence on 28 April 1976. These values gave strong indications of what was to follow and indicated that the atmosphere was already sufficiently un-

stable for severe convection to take place. The SWEAT indeces were 588 and 500, respectively, well above the threshold level for severe thunderstorms. Only the environmental wind field was weak in support of severe convective activity. Although veering was evident in the lowest 3 km, the middle layer (3 to 8 km) winds backed with height. Shear in both instances was weak, with values of 1.3×10^{-3} sec^{-1} for the 800 to 200 mb level for MAF and 9.4×10^{-4} sec^{-1} for the 700 to 200 mb level for AMA. These are well below severe-related values given by Marwitz (1972a,b,c). However, with such strong instability pushing toward severe storm development, it is likely that only mild shear is necessary for the generation and growth of severe storms in this area (Miller, 1972).

The storm was in its dissipating stage, as indicated in Figure 7, prior to the occurrence of hailstones measuring one and three-quarter inches (4.5 cm) in diameter. The storm height was less than 40,000 ft during radar observation, but the top was within 5,000 ft of the tropopause at the time of initial observation. Based on the results of Inman and Arnold (1961), the storm height represents a 20 per cent chance for three-quarter inch hail in Texas. Data on the 30 dBz top and the height of the Z_e max above the freezing level suggest a storm whose support has vanished and is reverting

to a non-severe storm. Lemon's (1977a,b) argument of the most severe weather occurring during collapse are borne out in this single-cell storm case.

The severe storms of 23 April 1976 also reflect the instability of the atmosphere. Total Totals values of 61 and 57 and SWEAT indeces of 557 and 397 at MAF and AMA, respectively, only 1.5 hours prior to severe storm occurrence, reveal the nature of the atmosphere. Further, the vertical wind structure indicated a strong veering condition in the lowest 3 km, weak veering in the layer from 3 to 6 km, then strong veering in the upper layers. Shear values are comparable to those given by Marwitz (1972a), with a value of 3.9×10^{-3} sec^{-1} calculated between 800 and 250 mb.

The occurrence of severe weather again follows the collapse of the storm, indicated by the decreasing heights of both the echo top and the 30 dBz top as shown in Figures 8 and 9. Storm 1 also shows a pronounced decrease in the reflectivity, while storm 2 reveals an increase of this parameter. The height of Z_e max is at the freezing level in both instances, and radar indicated that both storms were single-cell storms.

The other severe storms investigated showed similar patterns of decay and subsequent severe weather, and the environmental conditions varied, as given in Figures 2 and 10 and Table 6.

TABLE 6

SUMMARY OF SEVERE THUNDERSTORM

ENVIRONMENTAL CONDITIONS

Location Date/Time	Rawinsonde Date/Time	Total Totals	SWEAT Index	Max Shear*
Moody AFB 11 May 2000Z	BHM/72229 11 May 1200Z	43	145	3.3
Fort Riley 4 Sep 2240Z	TOP/72456 4 Sep 1200Z	49	335	- .16
	DDC/72451 4 Sep 1200Z	40	162	- .43
Fort Riley 24 Jun 2000Z	TOP/72456 24 Jun 1200Z	45	153	1.1
	DDC/72451 24 Jun 1200Z	46	128	2.0
Reese AFB 21 May 2030Z	AMA/72363 21 May 1200Z	48	258	.78
	MAF/72265 21 May 1200Z	48	315	2.3
Reese AFB 25 May 0300Z	AMA/72363 25 May 0000Z	44	330	3.3
	MAF/72265 25 May 0000Z	64	552	4.5

*Shear in units of 10^{-3} sec^{-1}

Results of these analyses demonstrate that although a wind field which veers with height and is sufficiently sheared is a factor in severe storm development, severe weather occurs without this factor. However, the strongest and most destructive storms occur in an environment in which the wind field veers with height and is sheared. This, plus high instability, leads to a very strong likelihood for severe storm development. These environmental factors must also be considered when a thunderstorm is observed on radar and the combined information from the meso and synoptic scale must be used to ascertain the likelihood of any storm becoming severe.

CHAPTER V

SUMMARY AND CONCLUSIONS

The data set of sample thunderstorms in this study was biased in favor of severe occurrences due to the criteria established for recording observations. However, the number of storms which were verified as severe was exceedingly small. These results may be due to one of several factors: 1) Data gathered by AWS units was biased by the prevailing operational workload; 2) Verification data were incomplete; or 3) Insufficient verification data were available to define the severe storms. If the study was hampered by the data gathering technique, then operational units cannot be expected to offer any better data in the future unless operational workloads diminish significantly, an unlikely prospect.

If the fault lies in the verification scheme, then possible improvements may be made. Previous studies, such as those of Donaldson (1958, 1959, 1960, 1961), Geotis (1961, 1963), and Inman and Arnold (1961), relied not only on a centralized compilation of severe weather reports, but also used local sources, such as spotters, public reports, and the newspaper accounts in the regions of interest to verify occurrences of severe weather. The method of using newspaper accounts was attempted in

this study, but due to the time lag between occurrence of the severe weather events and analysis, and the wide distribution of occurrences, this method was not feasible. Wright, in an unpublished AWS/5th Weather Wing report, used the Storm Data log to verify severe storm occurrences; however, his criterion for verification was an occurrence within 120 nm of the radar, while this study demanded an occurrence within 60 nm and within 30 minutes of a recorded observation. Based on these requirements, the NSSFC SELS log was used in this study for verifying severe weather events and identifying severe thunderstorms. The best method of verifying severe weather events is the local observation. Therefore, if further studies of this nature are undertaken it is recommended that severe weather events be verified locally and that analysis be accomplished afterward at a central facility.

This investigation, was based on relatively few severe storm occurrences. Nevertheless, it has shown that the 30 dBz height, especially when correlated with thunderstorm tops or the tropopause height, may be an effective radar parameter for identifying severe storms. The precise CSI for this technique remains to be determined, but it seems to be significantly better than parameters currently used by operational units for identifying severe storms. Lemon (1977b), quoting the results of Foster (1976), found that current National Weather

Service parameters and methods of identifying severe storms yield a CSI of .13, with a POD of .47 and a FAR of .85. Although CSI values listed in Tables 2 through 5 are not to be taken at face value, the rank ordering technique shows that the 30 dBz parameter may be much more reliable for identifying severe thunderstorms than current techniques. It is recommended that local studies be undertaken to assess the actual CSI, FAR, and POD values for this parameter and those parameters which incorporate it.

The 30 dBz height has also proven indicative of the strength of the central updraft of the thunderstorm. In the few instances where remarks were annotated to the observations, a high 30 dBz top was associated with a weak-echo region remark. It would prove enlightening to define the relationship, if any, between the height of the 30 dBz echo and the occurrence of either a WER or a BWER. The height of the 30 dBz echo gives a good indication of the severe weather potential of any storm, the height of which is dependent on the environmental setting of the storm and other atmospheric variables (e.g., the tropopause height).

The environment plays a key role in the likelihood for any thunderstorm developing into a severe thunderstorm. The few parameters which were investigated showed regional and seasonal differences, but in general these

differences were not large. Greater reflectivities and higher echo tops were found with storms occurring in the South, but more severe occurrences were reported in the Great Plains. The wind fields were found to vary with severe thunderstorms. However, when all environmental parameters were taken into account, they usually presented an environment compatible for severe storm development. Although environmental data were analyzed upstream and prior to severe storm occurrence, this does not necessarily represent the environment in which the storm developed. Miller (1972) discussed the fallacy of assuming a non-changing environment. However, these environmental data represent the state of the atmosphere at a time prior to severe storm initiation. Thus, just as Lemon (1977a,b) has developed a unified technique combining thunderstorm structure and radar signatures, it is important to realize that meso and synoptic scale data must be combined to aid the practicing meteorologist in identifying severe storms so that weather warnings can be issued.

This study was initiated to update methods of identifying severe storms and to assess the regional and seasonal differences in radar parameters. In the first instance this study has been successful, identifying the 30 dBz height as a possible candidate for a method of severe storm identification. The establishment of geographical

and seasonal variations in severe storm parameters was not successful, however, due to a lack of verified severe storm occurrences. The investigative meteorologist is still a long way from completely understanding the mechanisms which initiate and sustain severe convective activity. The operational meteorologist on the other hand, is required to issue severe weather warnings based on severe storm identification techniques by using conventional radar data. These techniques require continuous updating and revision. This study indicates that better identification techniques are feasible using current equipment.

APPENDIX A

THE RADAR EQUATION

The usefulness of radar investigations of thunderstorms is based on the ability of radar to detect energy backscattered from a target. For thunderstorm surveillance radars the targets are hydrometeors of sufficient size (see Appendix B). The basis for inferences of the nature of the targets and its backscattered energy is the radar range equation which relates the received power at the antenna to the backscatter cross-section of the target.

Consider first a point target (after Battan, 1973 and Rogers, 1976). Let the peak transmitted power of the radar be given by P_t. The incident flux intercepted by a target a distance r from the source, assuming isotropic scattering, is given by:

$$S_{iso} = \frac{P_t}{4\pi r^2} \qquad \text{(A-1)}$$

However, a radar antenna scatters directionally, focusing the transmitted power into a cone. The ratio of the actual power flux density which falls upon a surface of given area to the power flux density that would fall onto the entire spherical surface from an isotropic source is the antenna axial gain, defined by

$$G \equiv \frac{S_{inc}}{S_{iso}}$$

Substituting into (A-1) for the incident flux,

$$S_{inc} = \frac{G\ P_t}{4\pi r^2} \qquad \text{(A-2)}$$

Let the target have cross-sectional area A_t; then the total power falling on this area is given by

$$P_{inc} = S_{inc}\ A_t$$

Substitution into (A-2) yields

$$P_{inc} = \frac{G\ P_t\ A_t}{4\pi r^2} \qquad \text{(A-3)}$$

If the target now backscatters isotropically, then the energy flux leaving the target which falls on the antenna, becomes

$$S_r = \frac{G\ P_t\ A_t}{(4\pi r^2)^2} \qquad \text{(A-4)}$$

However, most targets do not radiate isotropically, but have preferred directions in which they radiate. To account for this phenomenon we introduce the radar backscatter cross-section of the target, σ. In general $\sigma \neq A_t$.

If the flux, S_r, strikes an effective area of the antenna, A_e, then the total power received at the antenna is given by

$$P_r = \frac{G\ P_t\ A_e \sigma}{(4\pi r^2)^2} \qquad \text{(A-5)}$$

The antenna gain and the effective antenna area, or antenna aperture, are related by

$$G = \frac{4\pi A_e}{\lambda^2}$$

Substituting for A_e in (A-5), we find

$$P_r = \frac{G^2 P_2 \sigma \lambda^2}{(4\pi)^3 r^4} \qquad \text{(A-6)}$$

This is the radar equation for a single target of radar backscatter cross-section σ. However, meteorological targets are hydrometeors distributed throughout the entire volume of a thunderstorm. Some of these targets are simultaneously illuminated by the radar beam. The volume containing these targets is the contributing volume, defined by the horizontal and vertical beam widths and the pulse length of the radar. The contributing volume is given by

$$V_c = \frac{\pi \theta_{\omega_r} \phi_{\omega_r} h}{8} \qquad \text{(A-7)}$$

A contributing volume is depicted at a range r in Figure A-1, where θ_ω is the horizontal beam width

ϕ_ω is the vertical beam width

h is the pulse length

r is the range of the target from the radar.

An important assumption made in all radar work is that the contributing volume is completely filled with

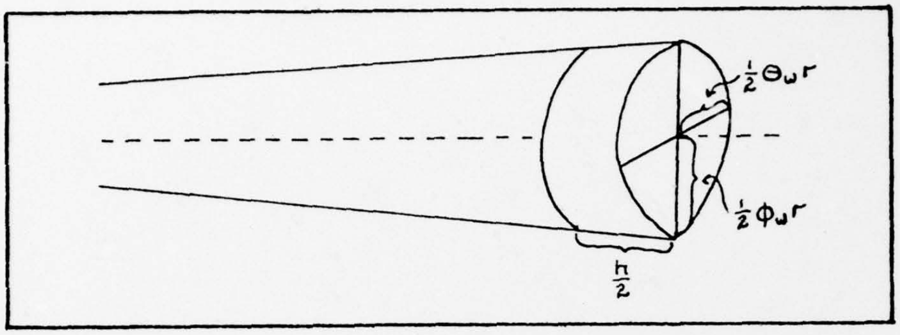

Figure A-1. The contributing volume of a radar beam at a range r.

scatterers. This assumption is acceptable when beam widths are small or if the range is small, but becomes increasingly unacceptable when wider beam widths are employed at longer ranges.

Since meteorological targets move randomly during times of illumination, the instantaneous power of the fluctuating signal depends on the arrangement of the scatterers. If these movements are averaged over 10 m/sec, however, the average power may be obtained. We sum the individual scattering cross-sections in the contributing volume, so that

$$\sigma = \sum_{i=1}^{n} \sigma_i$$

Substituting into (A-6) yields

$$\bar{P}_r = \frac{P_t \, G^2 \, \lambda^2}{(4\pi)^3 \, r^4} \sum_{i=1}^{n} \sigma_i \qquad \text{(A-8)}$$

Multiply the average cross-section by the trivial ratio V_c/V_c, so that

$$\sigma = V_c \frac{\sum_{i=1}^{n} \sigma_i}{V_c}$$

We define the radar reflectivity as:

$$\eta = \frac{\sum_{i=1}^{n} \sigma_i}{V_c} \qquad \text{(A-9)}$$

Substitution into (A-8) yields

$$\bar{P}_r = \frac{P_t\, G^2\, \lambda^2\, V_c\, \eta}{(4\pi)^3\, r^4}$$

Now introducing (A-7), we have

$$\bar{P}_r = \frac{P_t\, G^2\, \lambda^2\, h\, \theta_\omega\, \phi_\omega\, \eta}{8(4)^3 \pi^2 r^2} \qquad \text{(A-10)}$$

To this point an equal distribution of power throughout the beam has been assumed. However, Probert-Jones (1962) found the actual distribution to be quasi-Gaussian and used a correction factor to account for the discrepancy. Using the Probert-Jones correction, (A-10) becomes

$$\bar{P}_r = \frac{P_t\, G^2\, \lambda^2\, h\, \theta_\omega\, \phi_\omega\, \eta}{1024 \ln 2\, \pi^2\, r^2} \qquad \text{(A-11)}$$

Consider the hydrometeors to be perfect spheres whose radius is small compared to the radar wavelength. The Rayleigh scattering approximation is valid if $R < 0.1\lambda$. In this case only the electric dipole of the backscattering cross-section expression need be considered. The backscattering cross-section of a spherical drop from Mie theory is given by

$$\sigma = \frac{\pi a^2}{\alpha^2}\left[\left|\sum_{n=1}^{\infty}(-1)^n(2n+1)(a_n - b_n)\right|^2\right] \qquad \text{(A-12)}$$

Using only the first term of the expression for electric dipoles, given by

$$b_1 = \frac{-2i}{3}\left(\frac{m^2-1}{m^2+2}\right)\alpha^3$$

and substituting into (A-12) yields

$$\sigma_i = \frac{\pi a^2}{\lambda^2}\left|-2i\left(\frac{m^2-1}{m^2+2}\right)\alpha^3\right|^2$$

$$= \frac{\lambda^2\alpha^6}{\pi}\left|\frac{m^2-1}{m^2+2}\right|^2$$

$$= \frac{\pi^5 Di^6}{\lambda^4}\left|\frac{m^2-1}{m^2+2}\right|^2 \qquad \alpha = \frac{\pi D}{\lambda}$$

Now define

$$K \equiv \frac{(m^2-1)}{(m^2+2)}$$

so that

$$\sigma_i = \frac{\pi^5}{\lambda^4} \frac{\sum |K|^2 Di^6}{V_c} \tag{A-13}$$

Substituting (A-13) into (A-9) yields

$$\eta = \frac{\pi^5 |K|^2}{\lambda^4} \frac{\sum Di^6}{V_c}$$

We define the radar reflectivity factor as

$$Z \equiv \frac{\sum Di^6}{V_c} \tag{A-14}$$

so that the relationship between the reflectivity and the reflectivity factor is given by:

$$\eta = \frac{\pi^5}{\lambda^4} |K|^2 Z \tag{A-15}$$

Substitute (A-15) into (A-10) to give

$$\bar{P}_r = \frac{P_t G^2 \lambda^2 h \theta_\omega \phi_\omega \pi^5 |K|^2 Z}{1024 \ln 2 \, r^2 \lambda^4}$$

Regrouping terms, the meteorological radar equation is:

$$h = ct$$

$$\bar{P}_r = \left[\frac{\pi^3 c}{1024 \ln 2}\right] \left[\frac{P_t G^2 t \theta_\omega \phi_\omega}{\lambda^2}\right] \left[\frac{|K|^2 Z}{r^2}\right] \tag{A-16}$$

The first term is a constant; the second term is dependent on the characteristics of a given radar set and is also constant for that radar; the last term is dependent on the nature of the target, the medium of propagation, and the distance travelled.

When measurements are taken by radar, many of the assumptions made in the derivation above are not strictly applicable, the least applicable being the Rayleigh approximation. To circumvent this problem, meteorologists have defined the equivalent radar reflectivity factor, Z_e. Z_e is the summation per unit volume of the sixth power of the diameters of spherical water drops in the Rayleigh scattering region which would scatter back the same power as the measured reflectivity. Then, strictly, (A-16) becomes

$$\bar{P}_r = \left[\frac{\pi^3 c}{1024 \ln 2}\right]\left[\frac{P_t G^2 t\, \theta_\omega \phi_\omega}{\lambda^2}\right]\left[\frac{|K|^2 Z_e}{r^2}\right] \qquad \text{(A-17)}$$

This is the form of the radar equation most commonly used in the scientific community.

APPENDIX B

EFFECTS OF RADAR WAVELENGTHS

Meteorological radars detect liquid and frozen hydrometeors, with the detection capability of the radar dependent on its wavelength, minimum discernible signal level, and the distance of the target from the radar. The minimum detectable particle sizes for radars used for thunderstorm surveillance and investigation are given in Table B-1.

TABLE B-1

MINIMUM DETECTABLE PARTICLE SIZES FOR THREE METEOROLOGICAL RADARS

Radar	Wavelength (cm)	Range (nm)	Minimum detectable size* Liquid	Ice Crystal
AN/CPS-9	3.2	10	24	77
AN/CPS-9	3.2	50	42	131
AN/FPS-77	5.4	10	31	98
AN/FPS-77	5.4	50	53	167
WSR-57	10.5	10	29	91
WSR-57	10.5	50	50	155

*All sizes are given in units of mm x 10^{-3}.

Attenuation plays a significant role in the amount of backscattered energy available at the receiver. The problem of selective absorption of electromagnetic energy

bands becomes very important when liquid water is considered. The 1.35 cm water absorption band borders on the wavelengths of meteorological radar and wing absorption can significantly affect the interpretation of echoes perceived on the various displays.

The effects of attenuation due to intervening precipitation was determined by Gunn and East (1954) and is summarized by Battan (1973). The amount of attenuation due to intervening precipitation is given in Table B-2. In general, attenuation by liquid precipitation may be neglected for the WSR-57, may have to be considered for the AN/FPS -77, and must be accounted for in the interpretation of AN/CPS-9 data.

TABLE B-2

PRECIPITATION ATTENUATION*

OF THREE METEOROLOGICAL RADARS

		Drop Size Distribution	
Radar	Wavelength	Marshall-Palmer	Mod. M-P
AN/CPS-9	3.2 cm	0.0122-0.0198+	0.0144
AN/FPS-77	5.4 cm	0.0030-0.0040+	0.0031
WSR-57	10.5 cm	0.0009-0.0007+	0.00082

*Attenuation measured in units of dB/km/mm/hr.

+Two values of attenuation based on rainfall rates of 2mm/hr and 50mm/hr, respectively.

APPENDIX C

TOTAL TOTALS AND SWEAT INDECES

The Total Totals index is a stability index for the atmosphere and is calculated using temperatures and dew points of the 850 and 500 mb levels. It is a combination of the vertical totals (850 - 500 mb dry bulb temperatures) and the cross totals (850 mb dew point - 500 mb dry bulb temperature). Thus

$$\text{Total Totals} = T_{850} + T_{d850} - 2T_{500}$$

A vertical totals value of 26 is indicative of thunderstorm occurrence. The value of the cross totals indicates the potential severity of the storm. Table C-1 defines these values.

TABLE C-1

TOTAL TOTALS INDEX AND SEVERITY*

Total Totals	Forecast Severity
below 44	non-severe
44 - 48	hail less than .5 inch winds below 50 knots
48 - 52	hail of .75 inch winds to 50 knots possible tornadoes
52 - 56	hail greater than .75 inch winds over 50 knots tornadoes likely

*based on Miller (1972)

The Severe Weather Threat (SWEAT) index was developed at the Air Force Global Weather Central (AFGWC) by Miller (1972) to assess the severe weather potential for large areas of the U. S. The index uses the stability parameters and the environmental wind field to predict the occurrence of severe convective activity. The formula for calculating the SWEAT index is given by

$$SWEAT = 12D + 20(TT - 49) + 2f_8 + f_5 + 125(S + 0.2)$$

where D is the 850 mb dew point in degrees C

TT is the Total Totals index

f_8 is the speed of the 850 mb wind in knots

f_5 is the speed of the 500 mb wind in knots

S is the sine of directional difference in the wind flow between 500 and 850 mb

A constraint is made that no term in the equation may be negative. If any term is less than zero, this term is set to zero.

The SWEAT index takes into account the low-level moisture, the stability of the column, and the vertical veer and shear of the wind field. The use of the SWEAT index to predict severe weather is given in Table C-2. It is important to remember that the SWEAT index only defines the severe weather potential. A release mechanism is required for activation.

TABLE C-2

SWEAT INDEX INDICATION OF SEVERE WEATHER

SWEAT index	Severe Weather Probability*
Less than 200	Highly unlikely
200 - 300	5 - 10%
300 - 400	10 - 35%
400 - 500	35 - 70%
500 - 600	70 - 95%
More than 600	Almost certain

*Percentages based on results of analysis of 102 severe storm cases by Miller (1972).

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BIOGRAPHY OF THE AUTHOR

Werner Helmut Balsterholt was born in Herne, Germany on 11 April 1947 to Heinrich M. and Helga M. Balsterholt. The family emigrated to the United States in 1955 and settled in Norridge, Illinois. He attended school to the third grade in Germany and completed his elementary education in several public schools in the Chicago area. He attended and graduated Ridgewood High School in 1964. He entered the University of Illinois at Navy Pier and subsequently Chicago Circle, where he graduated in June 1968 with a Bachelor of Science degress in Physics.

He enlisted in the United States Air Force in November 1968, was selected for Officer Training School in April 1969, and received his commission as Second Lieutenant in June 1969. He was selected to attend post-graduate school at Saint Louis University and completed the program for Basic Meteorology in July 1970.

He has served as detachment forecaster at Cannon Air Force Base, New Mexico, weather officer and briefer at Tan Son Nhut Air Base and Cam Ranh Bay Air Base, Republic of Vietnam, and wing weather officer at U Tapao RTNAB, Thailand. He served as wing weather officer, radar coordinator, and then Staff Weather Of-

ficer to the National Emergency Airborne Command Post (NEACP) of the Joint Chiefs of Staff and assistant Staff Weather Officer to the 89th Military Airlift Wing and the Office of the Presidential Pilot while at Andrews Air Force Base, Maryland.

He was chosen by the Air Force Institute of Technology to attend Saint Louis University to pursue the degree of Master of Science in Meteorology in May 1976.

He is a student member of the American Meteorological Society and his only published work was in the area of radar meteorology within the Air Force. He is currently serving in the United States Air Force with the rank of Captain.